

History of Transformers

The apparatus Michael Faraday constructed in 1831, by which he invented electromagnetic induction, contained all basic elements of transformers: two independent coils and a closed iron core. Nevertheless, another 54 years passed before the appearance of the transformers and transformer energy distribution networks that are generally used today.

During that half-century, several induction devices were constructed that were similar to the heavy-current transformers, but they were different in their construction or operating method. On the basis of these differences, the transformer must be regarded as an independent invention. However, to draw the line between the experimental apparatus of laboratories and the heavy-current transformers, we must consider the development process from Faraday's experiment to heavy-current application. This article summarizes the history of transformers from their beginning until 1885. This is when three young Hungarian engineers of the Ganz factory in Budapest, Károly Zipernowsky, Miksa Déry, and Ottó Bláthy constructed the first transformers and built the first transformer system with parallel distribution.

Direct-Current Induction Devices

Faraday's apparatus was designed to study whether a direct current (dc) and the magnetic field that was produced by a dc coil induced voltage in another coil. It took several years of experimentation for Faraday to realize that constant dc does not have such effect, but the change, the increase or decrease of the current, in fact generates voltage in the other coil. Naturally, the apparatus was fed by a dc galvanic battery, since no other power source was available at that time. Induction coils, which were operated by intermittent dc, were considered as dc devices, as the image of ac was unknown, and alternating-polarity voltage was considered unsuitable for practical purposes. This is understandable, since electrochemistry and electroplating were the first industrial applications of electricity. At that time, there were only dc devices, and the early magnetoelectric generators supplied dc. It is true that ac was induced in their coil, but, on Ampère's suggestion, it was converted into dc by mechanical commutator from the outset.

Induction coils were used to produce much higher voltage than galvanic batteries. In 1832,

From experimental devices of the 1830s to the first transformer systems of the 1880s

when self-inductance was invented, Joseph Henry noticed that with the interruption of current very high (several hundred volts) voltage is induced in the coil due the rapid flux change. The physiological effect was similar to that of the shocks of the Leyden jars which were charged with friction generator, but the new device was more reliable and cheaper. Continuous operation was en-

sured by various vibrators, first with hand-driven apparatus (1835 Callan and Neeff, 1837 Sturgeon), then with automatic electromagnetic vibrator, the ancestor of the current electric bell (1838 Bachhoffner and Page, 1839 Wagner). The devices were used for medical purpose, for electrotherapy.

The effect (i.e., voltage) could be increased by two-coil converter. In 1836, Callan prepared an inductor in which he led the intermittent current of the battery into a primary coil with low number of turns, while the secondary coil was made from thin wire, with high number of turns. The iron core was a ductile iron bar. In 1838, Page from America, and, in 1842, Masson from France were able to generate several kV with similar devices; voltage could spark over an air gap of several millimeters between the poles of the secondary coil. These were the first spark inductors.

Spark Inductors

The spark inductor was a high-voltage pulse transformer, but

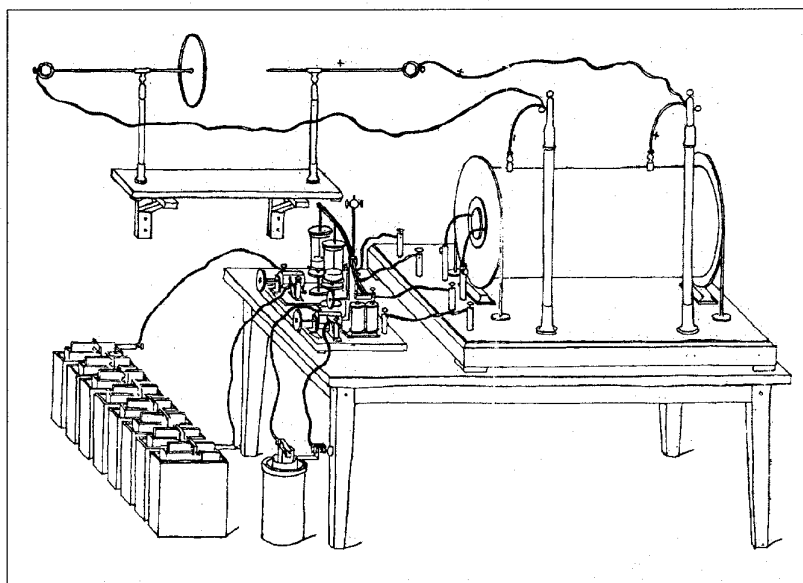


Figure 1. Ruhmkorff's inductor drawing from 1871 in the operating instructions supplied with the device

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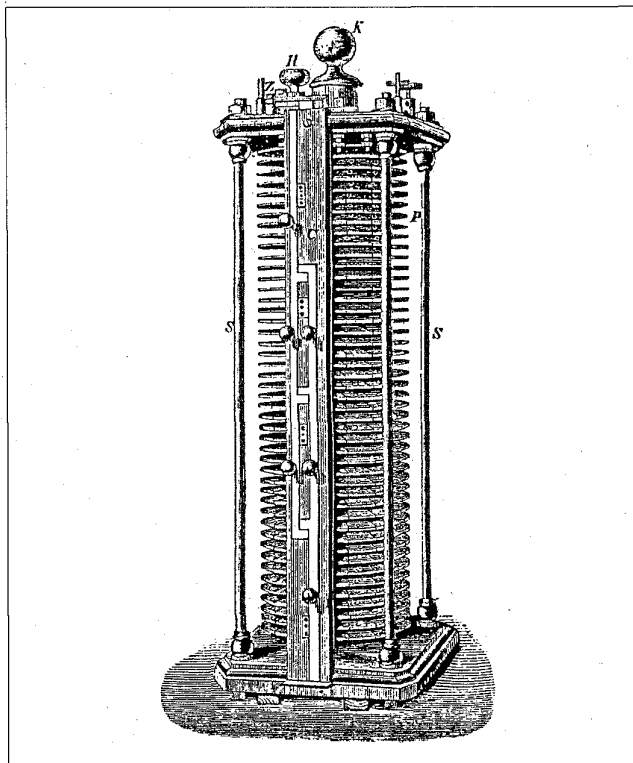


Figure 2. The secondary generator of Goulard and Gibbs (ETZ 1885, page 291)

it cannot be identified at all with the heavy-current transformer, and even less with its application. However absurd it may sound from the physical aspect, spark inductors were regarded as dc devices at that time! It is not so surprising with regard to the primary circuit, since it was fed by intermittent dc, but even more strange is the fact that the secondary coil had both a positive and a negative pole. Transformers cannot supply continuous dc, since the flux of the iron core should continuously increase. Naturally, this is impossible. Of course, ac is produced in the secondary coil of the spark inductor, but it has an asymmetric wave form. When turning the battery on, long-time but low-amplitude half-wave is induced; when breaking it, short-time, but high-peak voltage is induced. Starting voltage can hardly be felt. When a spark gap is also present in the circuit, only the break peak voltage can produce current, so dc flows in the secondary circuit. This way, the positive and negative pole can already be interpreted. This strange behavior of the spark inductor explains the fact that X-ray tubes were not operated by an ac transformer but by a spark inductor in the first decades of X-ray technology, when the high-voltage rectifier had not been invented yet.

The development of spark inductors promoted the construction of the later transformers in the area of production technology rather than theory. The first inductors only provided sparks that were a few millimeters long, but, in 1853, Daniel Ruhmkorff increased the spark length first to 200 mm then to 450 mm by improving the vibrator and the insulation. Real competition started to increase spark length. Apps from England was able to produce 1,070 mm long sparks in 1876. The biggest inductor was constructed by Klingelfuss from Switzerland, his inductor that was presented at the World Exhibition in Paris in 1900 produced 1,500 mm long sparks. After the turn of the century, the power of X-ray inductors exceeded several kW. Important

technical achievements were the vacuum impregnation of high-voltage coils, oil insulation, the disk-winding proposed by Pogendorff, and the application of laminated iron core. All these could be excellently used later when building high-voltage transformers. On the other hand, inductors were still characterized by rod-shaped open iron core, called free-pole design at that time. This layout was justified in case of inductors, but definitely delayed the development of ac transformers.

Initial Application of Alternating Current

In the 1850's, an application field of electricity in which there was no significant difference between dc and ac came to the forefront. This was electric lighting.

The flame-arc lamp was not a novelty, but had been considered a curiosity before. Humphrey Davy already noticed in 1802 that blinding arc was produced between the cable ends by the short circuit of the large galvanic battery of the Royal Institution. Soon he produced electric arc between carbon rods, so he managed to keep the lamp in operation already for a few minutes. In 1812, he introduced the new light source in public, but galvanic batteries ran down soon, thus practical application could not even be considered. More than 3 decades later, at the end of the 1840s, when high-power durable galvanic batteries could be produced, electric lighting came to the front again. The light of a flame-arc lamp was lit up on special occasions, to produce stage effects, and to solemnize special events. Carbon rods were regulated manually at first, then Foucault constructed an automatic electromagnetic flame-arc lamp regulator in 1848. The regulator was improved by several inventors in succession, so reliable apparatus could be produced that enabled the operation of the lamp for several hours without supervision. Electric lighting became general in lighthouses, harbors, and for night-time construction. However, lamps were not supplied by batteries then, but by magnetolectric generators driven by a steam engine.

Initially, dc generators were used, which already proved in the electroplating workshops, but soon it turned out that the generator without commutator, which is cheaper and operates more safely, is also suitable for flame-arc lamps. This started the practical application of ac. In the 1870s, Jablochhoff's flame-arc lamp, which definitely needed ac, gave a boost to using ac. The „Jablochhoff candle" was a simple and cheap flame-arc lamp without mechanic regulator. The arc burnt at the end of the parallel carbon rods, and advanced toward the foot as the

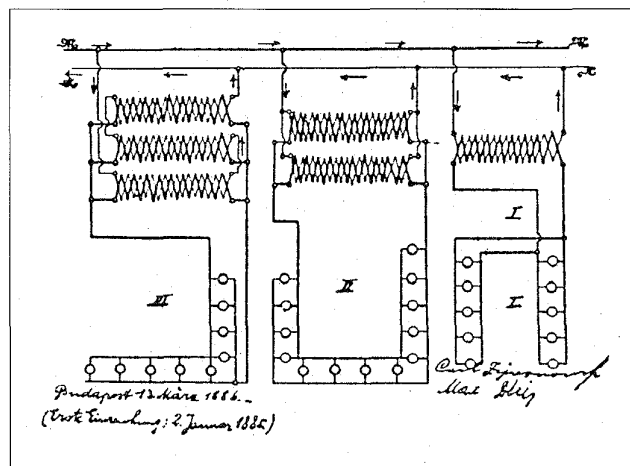


Figure 3. Parallel energy distribution and transformers in parallel, figured in an invention application of Ziperowsky

rods decreased. The condition of operation was the identical rate of burning of the rods, and this could only be achieved by ac supply.

Light Distribution

As arc lamps spread, the need emerged that a generator should not only feed one lamp but all the lamps along an avenue. This was called light distribution. The basic problem was the method of connecting lamps: in parallel or in series. Connecting consuming equipment in parallel seems natural today, but 120 years ago it was not so unambiguous. The reason is simple: arc lamps have 35-40 V voltage, and with this low network voltage the current of parallel consuming equipment and, due to this, the line losses are very high. Because of the voltage drop of the lines, the distance between the generator and the flame-arc lamps cannot exceed 100-200 m in a parallel system. Supply voltage of 1,000-1,500 V can operate 20-30 lamps in a series connection, the line of lamps may be several km long. This was true for both dc and ac systems. The problem was that only lamps with an identical current, that is, identical power could be used, and when a single lamp burnt out, the complete lamp line stopped lighting. Individual lamps should have been made independent of the serial network.

Jablochkoff was the first who realized in Paris in 1877 that instead of their direct connection into the serial main line, lamps should be fed through a two-coil induction device. He assumed that the different operation of lamps, which were galvanically separated, would not affect the other lamps. Although he was mistaken, he still managed to improve the operation of the system, and what is even more important, he started the research-development activity that led to the invention of the heavy-current transformer.

Secondary Generator System

In 1882, Goulard from France and Gibbs from England followed this path. Similar to Jablochkoff, they also used series connection, which enabled high-voltage power transmission and, through this, the bridging of long distances. This explains why success was chiefly achieved in the electrification of railway lighting. In 1884, a 12 km section of the underground in London, then the stations of the Italian Torino-Lanzo railway line, were equipped with electric lighting. In the latter case, the farthest lamp was at 40 km distance from the 2,000 V generator with 133 Hz frequency. Arc-lamps and Edison bulbs were both used for lighting.

They fell into the same theoretic error as Jablochkoff. They thought that the load change of the lamps fed by the induction device, which they called secondary generator, would not affect the current of the primary generator. It soon turned out that switching the individual lamps or lamp groups on and off entails significant current and voltage change, endangering electric bulbs which are sensitive to voltage fluctuation. They had to admit that the device could only be used for permanently operating luminaries, but in lighting flats and shops it could not compete with the parallel Edison system which became widespread by then.

In spite of the basic differences, many people consider the secondary generator as the first version of the transformer. The major difference is that it preserved a characteristic element of the Ruhmkorff inductor, namely, the open iron core. As Újházi from Hungary stated, the specialists of that time could hardly ignore the conception that inductive effect is caused by magnetic poles. Only the most qualified electricians adopted the graphic flux pattern, with self-closing lines of magnetic force based on

the theory of Faraday-Maxwell. This new approach led to the idea of replacing the protruding poles of the rotor by placing the coil into the grooves of the armature (drum armature) in case of rotating devices, and to the invention of the closed iron-core transformer in case of induction devices.

The secondary generator with open iron core and high stray reactance can best be compared to the welding transformer of our days. The terminal voltage which strongly decreases with loading was definitely advantageous in feeding flame-arc lamps. In fact, it was the imperfection of the secondary generators that enabled the operation of the system! In a series arrangement, the device operated as a current transformer. In principle, an ideal current transformer would „retransform” the break of the secondary circuit (blowing out of one flame-arc lamp) to the primary circuit just as if the primary line was broken. Now it is natural that the secondary terminals of an unloaded current transformer must be short-circuited. In the primitive apparatus, the stop of load did not cause such primary impedance increase that could have led to the blow out of the other lamps, and overvoltage exceeding the insulation strength was not produced in the secondary coil.

Transformer and Parallel Energy Distribution

The electric system that Edison built in New York in 1882 proved that wide-range public power supply can only be realized with permanent voltage network and the parallel arrangement of the consuming equipment. At the same time, it also became evident that large areas can only be supplied by high-voltage ac and transformer distribution. It happened at that time that three young engineers of the Hungarian Ganz factory, Károly Zipernowsky, Ottó Bláthy, and Miksa Déri reached a line the crossing of which led to the current layout of energy systems and the distribution transformer with closed iron core. The crucial step was taken in March 1885. This comprised three major elements:

- Rejecting series connection and connecting transformers that supply the consuming equipment groups in parallel to the main line
- Applying high-ratio transformers, separating high-voltage (1400-2000 V) wide supply network from low-voltage (100 V) consumer networks
- Developing a transformer with closed iron core, low drop (that is, the terminal voltage is almost independent of the load), and low loss.

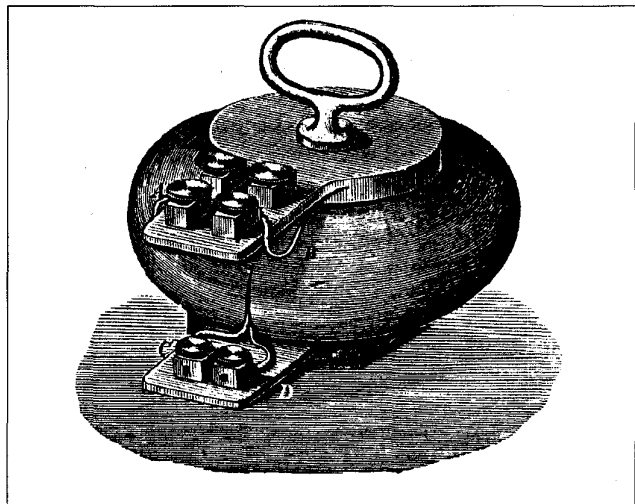


Figure 4. Shell-type Zipernowsky-Déri-Bláthy ancient transformer

The first introduction met with great success in 1885 at the Industrial Exhibition of Budapest, the indoor and public lighting of which corresponded to that of a small town of this age. The energy of the 100 Hz ac generator driven by reciprocating steam-engine traveled on 1,400 V to 12 pieces of 5 kVA shell-type and 4 pieces of 7.5 kVA core-type transformers which produced 60 V secondary voltage to supply 1,067 Edison incandescent lamps in parallel. Roads and large halls were lighted by ac arc lamps.

Although each system element is indispensable, the three engineers were many times referred to as the inventors of the transformer. Then this led to priority debates, since the closed

iron core or the different number of turns in coils alone were not novelties. The same applies to parallel distribution, since Edison was well-known for his dc system. Moreover, in 1883 Rankin Kennedy explained the advantages of parallel distribution by transformer, but he did not think of the fact that increasing the ratio of transformation increases primary voltage, by which loss can be reduced. In the lack of this realization, he deemed parallel distribution unsuitable because of the line loss.

The invention of Zipernowsky and his colleagues is not the transformer or its connection alone, but the system as a whole. However, the transformer has a significant role within this. At the same time, the inventors elaborated the shell-type and the core-type construction as well. The name transformer („transzformátor” in Hungarian) was also given by them. Special attention was paid to reducing leakage reactance to achieve small drop, that is, practically load-independent secondary voltage.

With shell-type iron core made of soft-iron wire without joint airgap, even the drop of small transformers with some hundred VA, designed to supply only 10-20 electric bulbs could be reduced to = 1.5 percent. The favorable structure of iron core also decreased open circuit losses to 1-2 percent. And this was important, since the opposers of parallel transformer distribution regarded open circuit losses as an intolerable deficiency of the system. The excellent construction enabled to reduce open circuit losses to a negligible level, so this was not a debating point any more. Good results were achieved with core-type transformers that had toroidal iron core, also reeled from soft-iron wire. Zipernowsky and his associates did not only find the theoretical solution, but they were the first to design and construct the transformer used in our days.

The Ganz factory immediately started the series production of transformers. The thousands piece was manufactured in 1889, and the ten thousandth one in 1899. The first transformers are now the precious pieces of museums. Ancient transformers made in 1885 can be found in Budapest, in the Deutsches Museum in München, the Technisches Museum in Vienna, the Ferraris Institute in Torino, and the Ford Museum in Dearborn, Michigan.

Previously, the fact that the first successful users of the system were regarded as inventors in several countries caused uncertainty. For instance, in the United States, William Stanley, put into operation his first transformer-operated system in Great Burrington in 1886. Stanley was a colleague of Westinghouse, the American pioneer of ac, and his reminiscence suggests that he might have gotten to the basic conception of the system in the summer of 1885, independent of the Hungarians. It was Ferranti who spread the system in England, as he improved the transformer with several inventions; moreover, in December 1885, he obtained a patent for connecting transformers in parallel. At that time, the invention of Zipernowsky was undoubtedly well-known in England, so this question does not concern technical history but patent right.

The invention of the transformer-operated system marked a new epoch in the history of electrical engineering. However, 1885 was not yet the year of victory, but the start of the decade-long competition between dc and ac. But this is another chapter in the history of electrical engineering.

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